Ad Hoc Sensor Networks

A New Frontier for Computing Applications

White Paper

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Intel Labs

Silicon systems that fight fires, predict earthquakes or locate lost hikers? Smart farmlands where silicon sensors in the earth help manage irrigation and fertilization? A "connected baby blanket" that prevents SIDS by monitoring an infant's health and vital signs? They're just a few of the applications that can result when Moore's Law meets wireless, self-organizing networks. See how Intel research is advancing this new computing paradigm.

Opportunities: *Proactive Computing, Connected Sensors*

Today, hundreds of millions of computing desktops and laptops are connected via the Internet. Tomorrow, hundreds of billions of embedded chips and sensing devices will be integrated into everything from key chains to baby cribs—and they'll all have the ability to compute, sense, and communicate.

At Intel's research facilities and elsewhere, silicon advances are achieving the predictions outlined by Moore's Law and are being combined with communications network research to enable thousands of small, embedded sensing devices to wirelessly connect and use virtually no power. The result is a new computing paradigm enabled by these ad hoc wireless sensor networks.

Ad hoc wireless sensor networks represent a core set of functionality needed to move into this next computing era when computers will be directly connected to the physical world and when computers begin anticipating what the users might want to do next—sometimes even taking action on their behalf.

This new paradigm not only improves productivity, but also can enhance safety, awareness, and efficiency, at both the individual and societal level. Imagine a crib that listens to a baby's breathing, a swimming pool that warns you if something falls in, a bracelet that informs you of an elderly parent's current health, or smoke detectors that guide emergency personnel—all connected and communicating critical data where it needs to go.

In the everyday world, ad hoc sensor networking will help enable electronic devices to recognize each other. Motors will tell you when they need maintenance, and your laptop will know when it has been dropped and needs repair.

The potential uses extend far beyond the home. Researchers are exploring the use of tiny devices that could be dropped by airplane over a large forest to find a lost child, or monitor the temperature and movement of a major forest fire. Crop conditions could be monitored down to individual plants. Sensors networks may also enable intelligent sensing of environmental conditions in homes and offices. Climate control could be more efficiently targeted to specific rooms, potentially reducing overall power consumption—a plus for the environment.

The role of humans changes in this new paradigm. Computers become more proactive, anticipating human needs and meeting them. The human is at the pinnacle and in control, instead of in the middle, shuttling the information between the real world and the computer.

Technology Challenges

There are a number of challenges to making ad hoc sensor networks a practical reality. These sensing devices, or motes, are actually wireless, embedded platforms that combine sensing, communication, and computation. The computers must not only be able to sense the world around them, but also to act upon it. And they need to be networked. The proliferation of silicon-based sensing devices could create a hundred fold increase above and beyond the growth of the Internet. There are a number of networking areas being researched today, including the creation of large self-organized networks, making the networks delay-tolerant for applications such as deep space or rapidly moving sensors, and abstracting the myriad of small-networked devices to make them accessible to computing applications.

Intel's fundamental focus on making Moore's Law a reality coupled with its ongoing silicon technology improvements are helping make sensor devices smaller and less expensive, and reduce their power requirements. However, many core challenges facing these new networks are "systems" challenges. For example, these new types of networks need to be easy to use and able to function without demanding human attention.

Intel Research Focus

The Intel Berkeley Research laboratory, located near the University of California, Berkeley, is leading research efforts working with the academic community and the industry to address many of these systems-level challenges. Among other things, this Intel Research Lab focuses on the architectural elements around these tiny, low-power wireless embedded platforms. This research also encompasses:

- The need for a flexible, open operating system.
- The networking technology challenges for large self-organized networks of sensor devices.
- Higher-level services needed to make it easy to develop robust applications for ad hoc sensor networks.

The Lab's researchers have already created a prototype research platform that's enabling researchers from industry

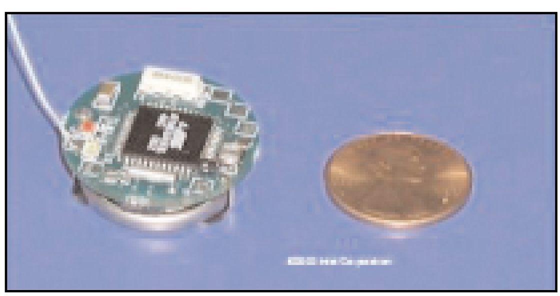

Figure 1. Intel advances in silicon technology will help drive sensor devices down to a cubic millimeter and smaller. Pictured above is a "dot-mote" currently in use and almost the size of a penny.

and academia to explore ways to use an ad hoc sensor net. The current platform measures 1-inch square, but in the future you can expect to see sensors only a cubic millimeter in size, and eventually as small as a speck of dust.

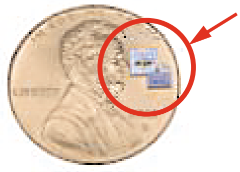

Figure 2. Researchers at the University of California, Berkeley, have demonstrated in the laboratory, devices only a few millimeters in size.

The ability to easily and cheaply deploy large self-organized networks of sensor devices is only useful if these devices can sense useful data. Intel is also working on ways to connect devices to the physical world, which means developing a whole new suite of sensors and actuators: sensors that can sense what's going on around them, actuators that allow the devices and computers to change the world around them, and in a size that will fit on these minute device platforms.

Intel is also working on precision biology—biochips. In addition to sensing dry, solid-state phenomena, our researchers are exploring the ability to sense wet substances, including biological materials and organic chemistry. This capability opens up every aspect of wetware, from health and pharmaceuticals to chemicals and refineries, and creates another new frontier for computing applications.

Research in Action

On August 27, 2001, researchers from the Intel Research lab at Berkeley and the University of California, Berkeley, demonstrated the largest self-organizing wireless sensor network. The network consisted of more than 800 low-power sensor nodes, each about the size of a quarter. The tiny nodes were hidden under 800 chairs in the presentation hall at the Intel Developer Forum Fall 2001 Conference. The nodes contained a 4-MHz, low-power microcontroller, 16 KB of flash instruction memory, 512 bytes of SRAM, ADCs, primitive peripheral interfaces, and a 256-KB EEPROM that served as secondary storage. Sensors, actuators, and an RF radio network served as the I/O subsystem. The nodes used the TinyOS, a component-based, event-driven operating system that ranges from a few hundred bytes for the scheduler to a few kilobytes for complete network applications.

For the demonstration, one application component provided network discovery and multihop broadcast. The nodes had a command packet that could be transmitted from any node that needed to become the root of a logical network. In the demo, this node was connected to an on-stage laptop computer. Nodes that received that packet selectively retransmitted the command, allowing the request to ripple over many levels and establish a self-configuring network.

Looking Forward

The new computing paradigm enabled by ad hoc wireless sensor networks will be key in making computing more proactive. Silicon-based sensors and ad hoc sensor networks represent exciting new technologies with broad societal impacts and a wide range of new commercial opportunities, and Intel is helping break down barriers that prevent these technologies from becoming a reality. Intel-led research is addressing many of the challenges of ad hoc sensor networks. In addition, as we continue to drive Moore's Law forward, advances in silicon technology, are reducing the size, cost, and power of sensor devices.

Expanding Moore's Law, Expanding the Power of Silicon

Moore's Law started as a simple observation. It has since become a beacon for the electronics industry, guiding the efforts of chip developers and showing the rate of progress we must maintain in order to remain competitive. Now, Intel is driving an expansion of Moore's Law to accommodate the rising complexity of silicon-based devices and the convergence of additional devices and technologies integrated onto the chip.

As Intel continues to fulfill Moore's Law, rising performance and lower costs, along with the convergence of such technologies as Microelectromechanical Systems onto silicon, are helping make technologies such as silicon-based sensor devices and ad hoc sensor networks an exciting reality. By applying the principles of Moore's Law to new classes of functionality, Intel's research is bringing about a new computing and communications geography, making these technologies more affordable and widespread, and opening the door to broad new areas of innovation. And it ensures that Moore's Law remains in effect for decades to come, through a combination of transistor count, complexity, and convergence.

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Papers by David E. Culler: www.cs.berkeley.edu/~culler/papers

About the Authors

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David E. Culler, a professor in computer science at U.C. Berkeley, has taken a leave of absence to work for Intel as the university director of the Intel Research lab at Berkeley. His research areas include parallel architectures, programming languages, and operating systems. Culler received his B.A. in mathematics from U.C. Berkeley in 1980, followed by an M.S. in computer science in 1985, and his Ph.D. in computer science in 1989 from Massachusetts Institute of Technology.

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